Characterization of friction joints subjected to high levels of random vibration

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ABSTRACT

When designing optical devices, the alignment of every element is integral to the proper functionality of the device. If any of these elements is secured by means of a friction joint, it is important to understand the limitations of the joint when vibrations (mainly during launch) occur; a phenomenon called "stick-slip" may happen and permanently displace joints relying on friction and cause optical misalignments. There is little to no data documenting the characteristics of the "stick-slip" phenomenon on friction joints under random vibratory motion. The test program was designed with the aim of gathering data that would broaden the understanding of the "stick-slip" phenomenon and among other things provide sufficient information to quantify the static coefficients of friction of several single-bolt friction joint material pairings.

This paper describes the test program in detail including test sample description, test procedures, and vibration test results of multiple test samples. The material pairs used in the experiment were Aluminum-Aluminum, Aluminum-Dicronite coated Aluminum, and Aluminum-Plasmadize coated Aluminum. Levels of vibration for each set of twelve samples of each material pairing were gradually increased until all samples experienced substantial displacement. Data was collected on 1) acceleration in all three axes, 2) relative static displacement between vibration runs utilizing photogrammetry techniques, and 3) surface galling and contaminant generation. This data was used to estimate the values of static friction during random vibratory motion when "stick-slip" occurs and compare these to static friction coefficients measured before and after vibration testing.

Keywords: Dicronite, Plasmadize, aluminum, stick-slip, random vibration, friction

1. INTRODUCTION

A “friction joint” is a bolted joint in which the friction alone due to high preload in the bolt is intended to prevent movement of the joint. A friction joint is designed so the friction force is high enough that no movement occurs across the joint. Such motion is unacceptable for some joints, such as when they are part of critical optical alignments. Stick-slip phenomenon is a static and kinetic friction dependent motion which is characterized by a jerky displacement followed by an abrupt stop between two solid sliding bodies[1]. This type of motion can be seen when a bow slides on a violin string, when brakes squeal, or when a piece of chalk squeaks on a chalk board[2]. More importantly, stick-slip may occur in any part of a machine in which two solid surfaces are able to slide on one another[3]. Vibrations in a machine may induce this type of slip-stick motion; this is generally undesired and hard to predict. Friction joints are particularly vulnerable when exposed to vibrations so special attention must be paid if these are to be used in designs, such as optical devices, where alignment is critical. There is little to no data documenting the characteristics of “stick-slip” phenomenon on friction joints under random vibratory motion.

Understanding the stick-slip phenomenon is especially important when designing friction joints that will undergo random vibratory motion. Space optical devices typically undergo violent random vibrations during launch and unwanted stick-slip motion may occur if mating materials are not chosen correctly. Equipment worth millions of dollars may be rendered useless in a matter of seconds because of stick-slip displacements. Due to the challenging nature of servicing and fixing devices in space, the utmost attention must be paid in every aspect of the design process. However, the lack of experimental data quantifying the effects of the stick-slip phenomenon hinders a designer’s ability to predict how friction joints will react during launch.

Accurately quantifying the coefficients of static and kinetic friction during stick-slip motion in friction joints is close to impossible. This undertaking is far more challenging than measuring these coefficients during smooth stop and go motion because of the unpredictability of stick-slip during random vibration. Furthermore, since the coefficient of kinetic friction is dependent upon velocity[1] during the sliding phase of slip-stick, measuring the particular velocity at which movement occurs is impractical. Thus, only crude estimates of these coefficients can be made. Perhaps these experimental challenges account for the lack of data in this field.

This lack of data led to a set of experiments in which friction joints, made up of three different material pairings (Aluminum-Aluminum, Aluminum-Dicronite coated Aluminum, and Aluminum-Plasmadize coated Aluminum), were exposed to random vibratory motion. Photogrammetry techniques to detect displacement were used, and acceleration data of three axes was gathered. The data collected through these experiments allowed for the estimation of the coefficients of static friction during random vibratory motion when stick-slip occurs. In order to help get a better understanding of how the stick-slip phenomenon affects the frictional characteristics in friction joints, experiments were carried out to determine the coefficients of static friction before and after vibration testing.

The friction joints that were tested were specifically designed to meet our test parameters. To achieve stick-slip displacement while maintaining reasonably low vibration levels, lever arms with large masses (located at the end of the lever arm) were used such that all forces would be resolved about a relatively small resisting circle far away from the center of mass of the joint (see Figure 1). The long lever arm allowed for a much lower input vibration. Furthermore, the long lever arm also allows for easy measurement of the small rotational displacements which occur at the friction joint during stick-slip. The sections that follow describe in detail, step by step, the test methods, procedures, and data collected for all friction joint pairings tested.

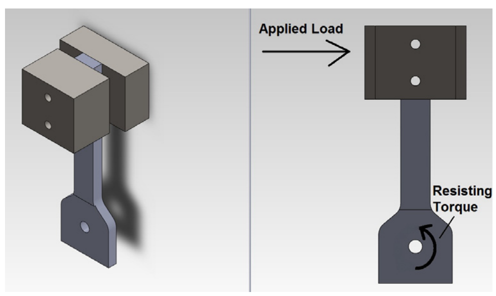


Figure 1. Lever arm with large masses showing applied force vs. resistive force.

2. FIRST STATIC FRICTION TEST

2.1 Methodology

The main components that make up the assembly for the first static test are similar to those of the random vibration test such that friction occurs in a similar fashion for both tests, thus simplifying the experiment and reducing the amount of parts needed. Thirty six single-bolt friction joint assemblies (see Figure 2) are used for the first static friction test. The main components of these assemblies are the static base and lever arm, which mate to make up the friction contact surfaces, and are attached by means of a bolt, washer and locknut. A load cell washer is used on each of the assemblies to measure the preload on the fastener. The static base and the friction sample are both made from aluminum (6061-T651). All contacting surfaces are cleaned and wiped with alcohol before mating.

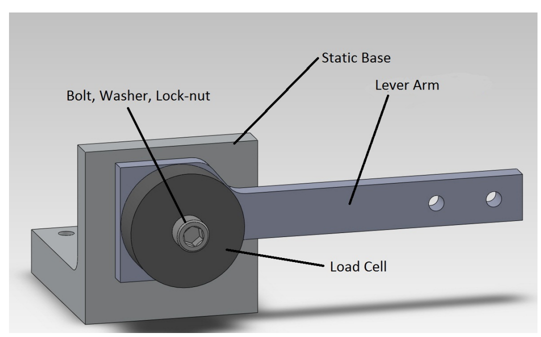


Figure 2. Static test assembly.

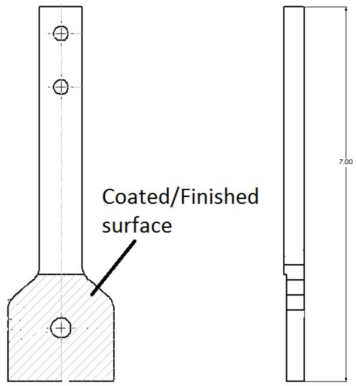


Figure 3. Lever arm.

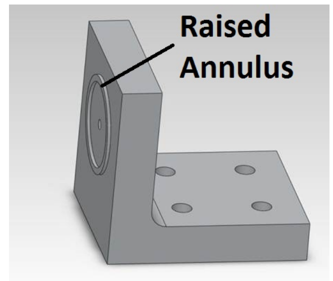
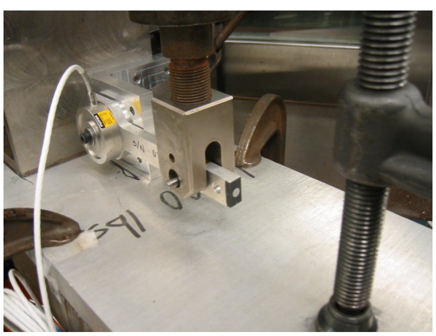


Figure 4. Raised annulus on static base.

The thirty six assemblies are each given a serial number and are divided into three groups of twelve, with every assembly being identical within each of the three groups. Each of the three groups consists of a different surface/coating pairing of Aluminum and Aluminum, Aluminum and Dicronite coated Aluminum, or Aluminum and Plasmadize coated Aluminum. Each coating is applied on the mating surface of the lever arm (see Figure 3). The static base has a raised annulus on its front surface. This annulus is the only area of contact between the lever arm and the static base (see Figure 4). It was decided to use this raised annulus, rather than two flat surfaces, to simplify the calculations and reduce uncertainty in load distribution.

Each group is preloaded to a pre-determined amount, the load cell (FUTEK Models FSH00433, FSH00415, and FSH00416) being used to insure accuracy. The Aluminum-Aluminum group is preloaded to 3500 lbs., the Aluminum-Plasmadize group to 2500 lbs., and the Aluminum-Dicronite group to 8000 lbs.



Each preload, as determined by the load cell read out, is recorded. The assembly is then loaded on an Instron tensile testing machine and the static base is clamped down to prevent any motion other than the radial swing of the sample (see Figure 5). The sample is then pulled until slip occurs—this point can be determined by looking at the load vs. displacement display on the tensile test machine computer (see Figure 6). This process is then repeated for every assembly of every group. The data obtained is used to determine the coefficient of static friction of each material pairing set.

Figure 5. (Left) Typical testing configuration for static friction test.

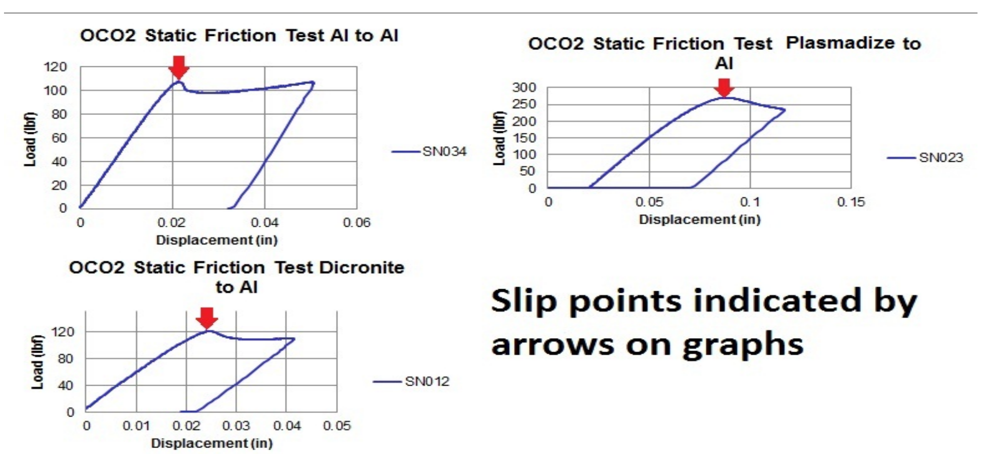


Figure 6. Typical sample load vs. displacement graphs showing slip points.

2.2 Data and results

Data was collected for all three assembly groups including the preload on each load cell, and the load required for slip (included in the load vs. displacement data). The data was then used to estimate the coefficient of static friction for each sample using Equation (1) in Section 6. The average coefficient of static friction for each group was then calculated (Table 1).

Table 1. Average coefficients of friction calculated for first static test.

Sample	Preload	Average Coefficient of Friction	Standard deviation
Dichronite	~8150 lbs	0.098	0.018
Aluminum	~3500 lbs	0.192	0.038
Plasmadize	~2600 lbs	0.704	0.021

3. RANDOM VIBRATION SLIP-STICK FRICTION TEST

3.1 Configuration

Some differences in configurations occur between static set up and the dynamic set up (see Figure 7). The biggest difference between the two test assemblies is the inclusion of masses which are fastened securely at the end of each lever arm. The purpose of these masses is to reduce the vibration levels required for stick-slip to occur. The same lever arms that were used for the first static friction test are re-used for this test. However, the contact area between the raised annulus of the dynamic friction base and the lever arm's coated surface is different than the contact area from the first static test because the raised annulus of these bases has a different diameter (see Figure 8). This is to ensure contact surfaces are undamaged. All contacting surfaces are cleaned and wiped with alcohol before mating. Dynamic assemblies are composed of two masses, a lever arm, a dynamic base, a load cell, two rubber hard stops, and the fasteners used to secure everything. Once again the assemblies are separated into three groups of twelve, with each group containing one of the three different material/coating pairs.

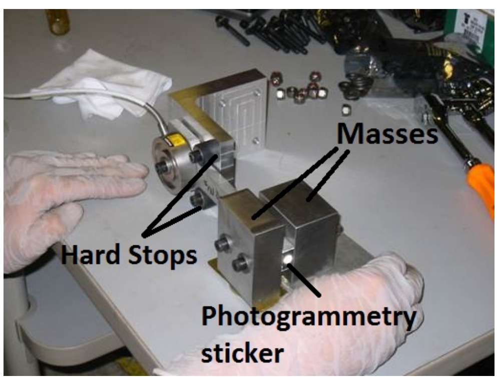


Figure 7. Dynamic test assembly

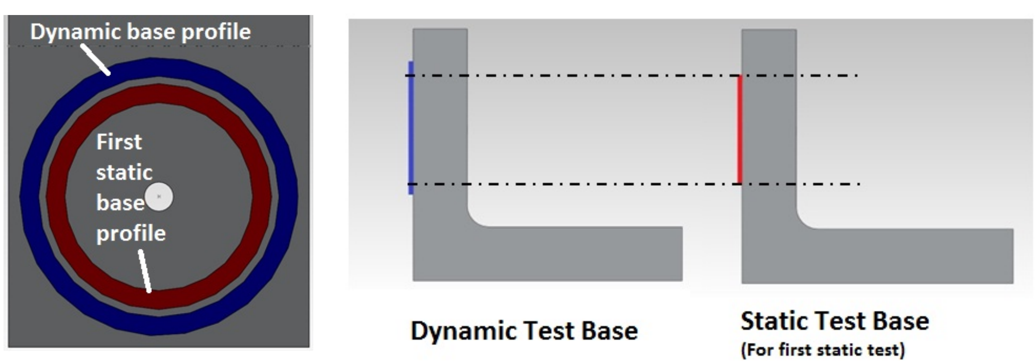


Figure 8. Annulus diameter comparisons between first static test and dynamic test.

Hard stops at either end of the lever arm are meant to prevent radial motion greater than 0.2” measured from the top of the masses. These keep samples from hitting one another during the vibration test since twelve dynamic assemblies are tested at the same time. However, during testing motion greater than 0.2” was never observed so the rubber stops did not come into play. During each test twelve dynamic assemblies are attached to a special vibration fixture that is designed to fit a shaker table.

Each group is preloaded to a pre-determined amount, the load cell being used to insure accuracy. The Aluminum-Aluminum group is preloaded to 3500 lbs., the Aluminum-Plasmadize group to 1000 lbs., and the Aluminum-Dicronite group to 8500 lbs. Note that preload for Aluminum-Plasmadize pair was increased and Aluminum-Dicronite pair decreased in order to allow all friction joints to experience stick-slip at approximately the same load level during vibration.

The vibration test article consists of three separate test configurations each containing a different assembly group (see Figure 9). The overall size of the test article is 18 inches by 18 inches by 10 inches tall. The estimated weight is approximately 95 pounds. The first configuration includes twelve samples of Aluminum and Dicronite coated Aluminum material pairings. The second configuration includes twelve samples of Aluminum and Aluminum material pairings. Finally, the third configuration includes twelve samples of Aluminum and Plasmadize coated Aluminum material pairings. Each configuration has identical interfaces to the shaker head. The configurations are subjected to one axis of vibration.

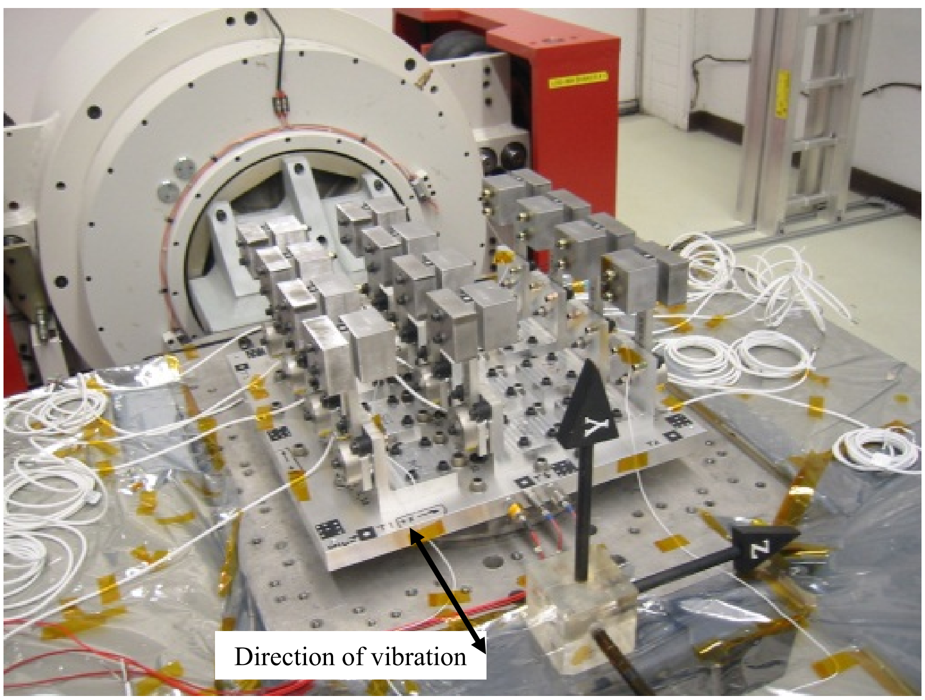


Figure 9. Typical test configuration showing twelve dynamic assemblies attached to the vibration fixture which is itself attached to the shaker head.

One response accelerometer is installed on each of four pre-selected samples near the center of gravity (C.G.) of each sample/mass assembly (see Figure 10). The triaxial accelerometers are mounted on the side of the test sample at a height that is approximately 4.75 inches above the load cell centerline.

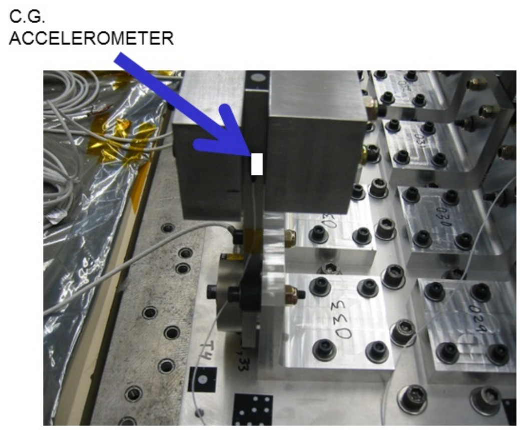


Figure 10. C.G. Accelerometer.

3.2 Photogrammetry

Notice also that each assembly has a white photogrammetry sticker at the top end of each sample (see Figure 7), and the vibration fixture has several patterned stickers (see Figure 9). These photogrammetric stickers serve as fingerprints with known light intensity values and are recognized by special software when photographed. The patterns on some of the stickers serve to create the correlations necessary to make distance measurements between all other stickers[4]. Relative distances between each lever arm and the vibration fixture are measured by means of photogrammetry. Photogrammetry uses special pictures (see Figure 11), which recognize light intensity levels, from different angles to calculate distances between several reference points by means of triangulation. This process is expedited by using special software.

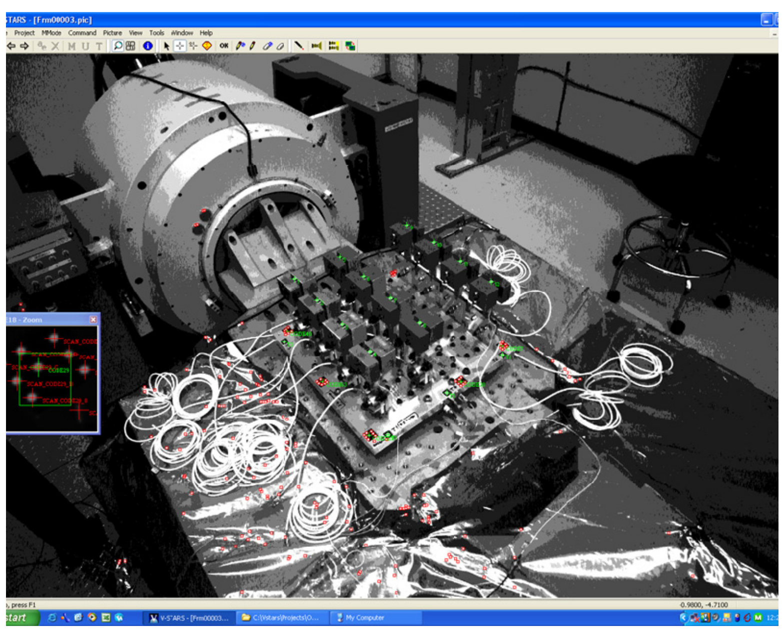


Figure 11. Typical photogrammetry photo showing software recognition of light intensity patterns.

3.3 Methodology

Before testing, a sinusoidal survey is used to validate the predicted modes and frequencies. A typical response plot is shown in Figure 12.

For each configuration, the random vibration level must be incrementally increased to cause stick-slip of the friction joints, and the position of each lever arm must be measured to determine if displacement has occurred after each vibration run. A vibration run is defined as a one minute long random vibration of a given dB level. If the lever arm moves more than 0.100 inches from its original position after a vibration run, the particular sample is declared as a failure but testing continues. The test levels are increased until all twelve lever arms have overcome their friction bolted joint or the test level has reached 0 dB.

Each configuration begins at -24dB and vibration levels are increased at 3 to 4 dB intervals until displacement of any lever arm greater than .03" is detected. After this point, test levels are increased by 2, to 1 dB intervals. This slow stepping method is intended to capture more accurately the load level at which stick-slip occurs.

Test levels were chosen such that the anticipated initial slipping would occur at -12dB, which is one quarter of the full level. These estimations were based on the coefficient of static friction as determined by the results of the first static test. However, during vibratory testing, levels higher than -12dB were passed, and at the highest levels of vibrations some samples still did not fail as predicted.

Measurements of motion are accomplished by means of photogrammetry. The random vibration test levels are different for each of the three configurations due to the difference in measured coefficient of static friction and preload levels (see Table 2). Originally, all test levels were the same but the preloads for each set had to be reduced in order to keep maximum vibration levels within the machine's limits. The random vibration levels are chosen to guarantee slipping of each sample. In reality, however, not all samples moved.

Table 2. Random vibration test levels.

Frequency	PSD levels (g^2/Hz)		
	Dicronite	Bare Aluminum	Plasmadize
20 Hz	0.0031	0.0105	0.0218
20 – 50 Hz	+6 dB/octave	+6 dB/octave	+6 dB/octave
50 Hz	0.0190	0.0650	0.1350
800 Hz	0.0190	0.0650	0.1350
800 – 2000 Hz	-6 dB/octave	-6 dB/octave	-6 dB/octave
2000 Hz	0.0031	0.0105	0.0218
Overall G_{rms}	4.87	9.00	12.98

Random vibration tests shall be conducted within the following tolerances:

-Spectral values: ±3 dB, measured in frequency bandwidths of 25 Hz or less.
-Wide band (grms) level: ±1 dB
-Frequency: ±5%
-Time: ±5%

The displacement and accelerometer data recorded is used to estimate values for the slip-stick static coefficient of friction.

3.4 Data and results

A typical response to the modal survey is shown in figure 12.

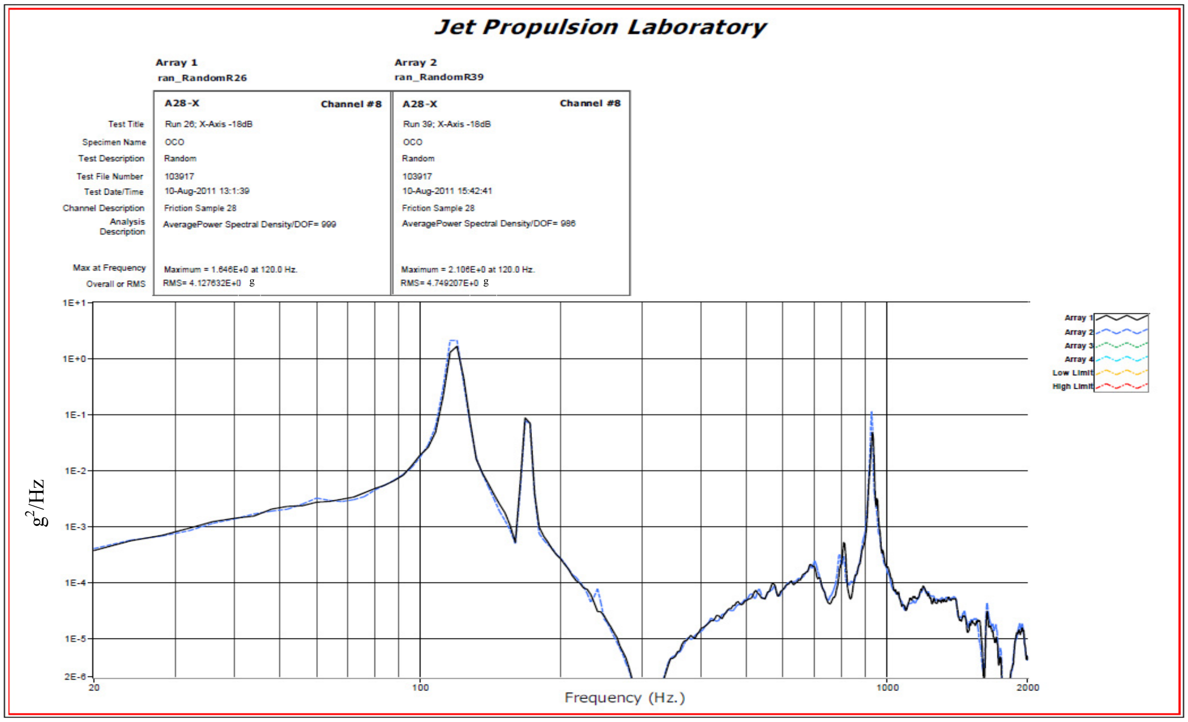


Figure 12. Typical response to modal survey.

Displacement data was collected for each configuration. Measurements were taken between each vibration run, and distances reported are relative to the initial location of each sample (see Figures 13-15). This data, along with the initial preloads and root-mean-square acceleration (GRMS) data (see Figures 16-17) on each sample were used to determine the coefficient of slip-stick static friction (see Table 3) using Equation (2) for the samples that were outfitted with accelerometers.

Table 3. Average coefficient of stick-slip static friction data.

Sample	Preload	Average Coefficient of stick-slip Static Friction	Standard deviation
Dicronite	~8500 lbs	0.149	0.009
Aluminum	~3500 lbs	0.336	0.088
Plasmadize	~100 lbs	0.866	0.059

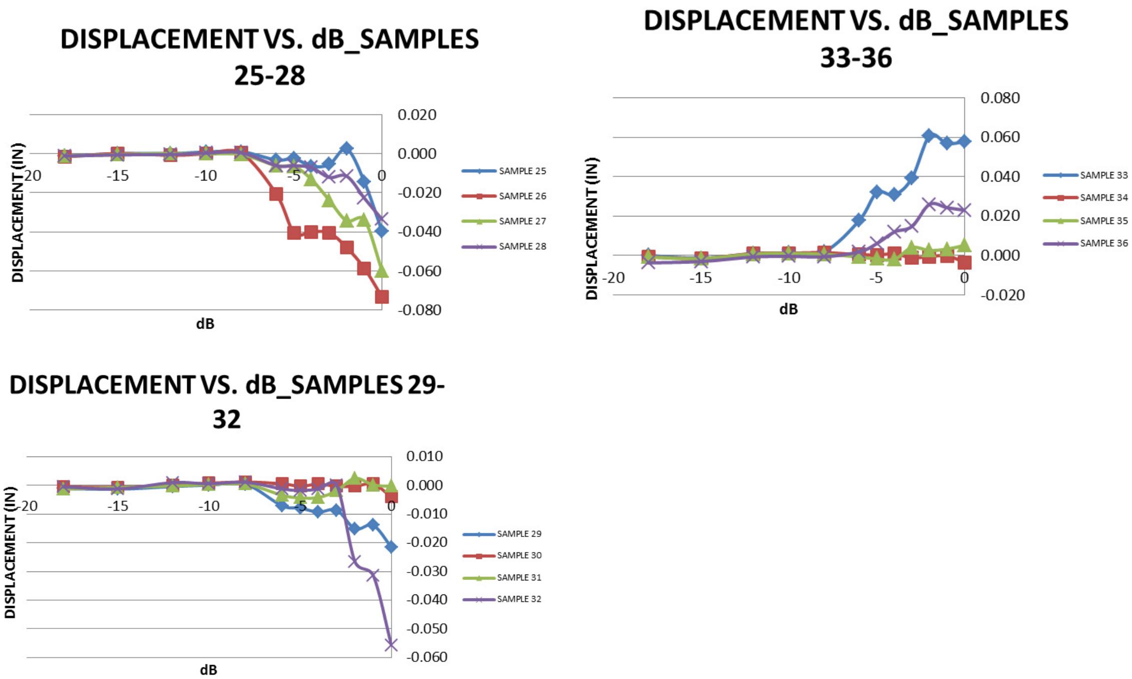


Figure 13. (Above) Aluminum-Aluminum graphs; samples 25-32.

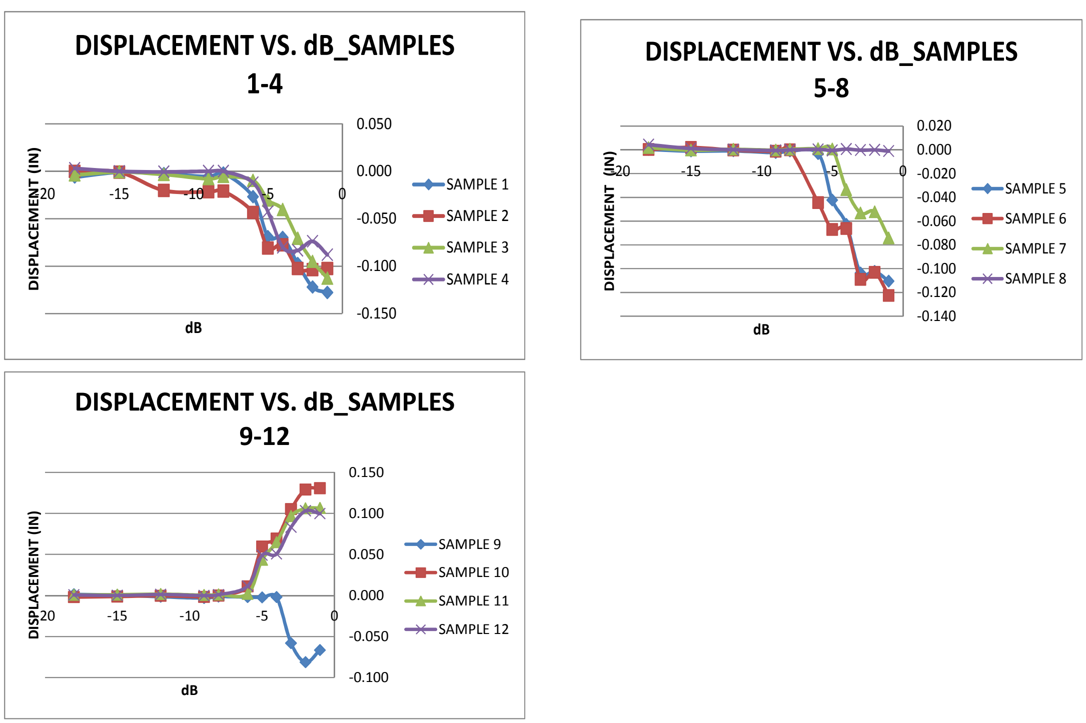


Figure 14. (Above) Dicronite-Aluminum graphs; Samples 1-12.

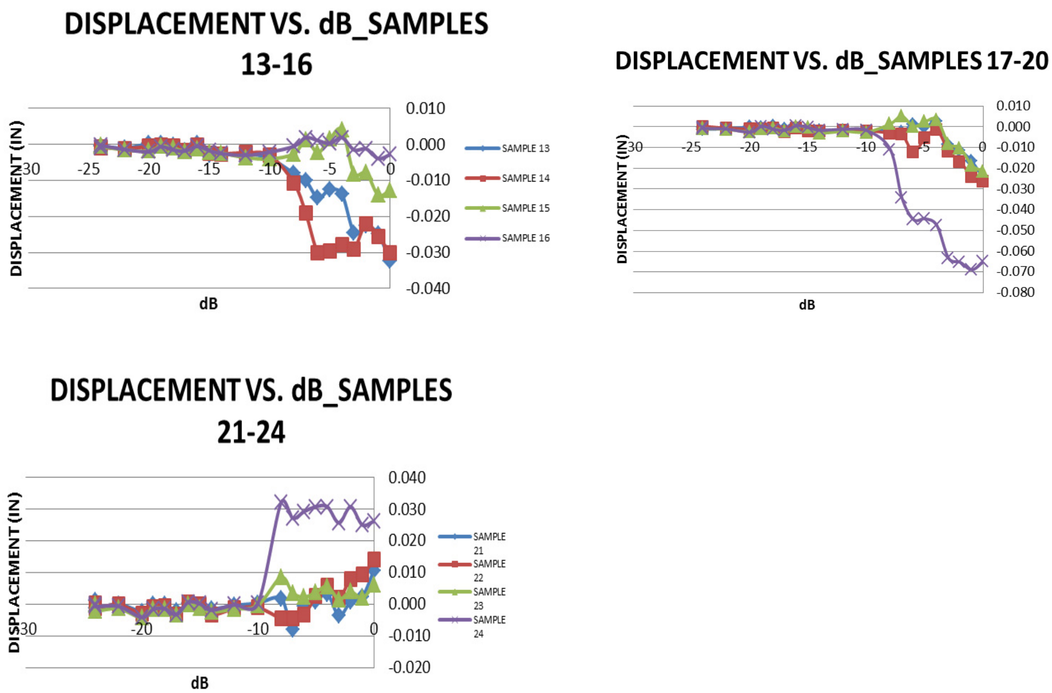


Figure 15. (Above) Plasmadize-Aluminum graph; Samples 13-24.

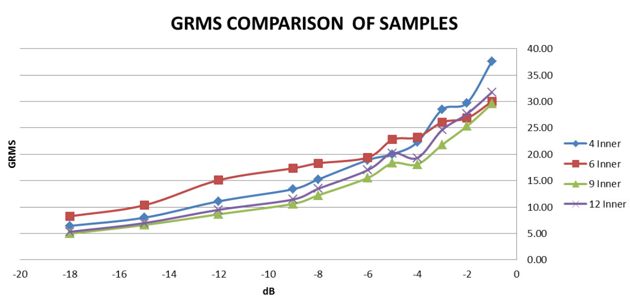


Figure 16. (Above) GRMS vs. dB Dicronite-Aluminum.

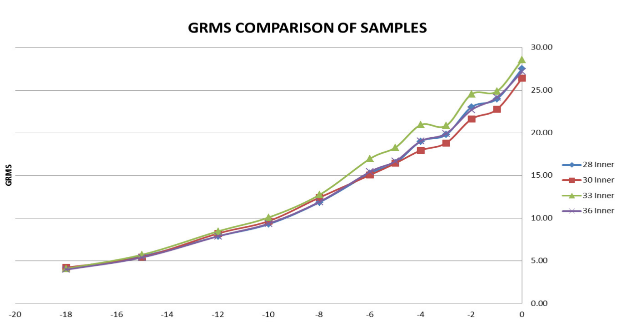


Figure 17. (Above) GRMS vs. dB Aluminum-Aluminum.

3.5 Discussion

The average values for the estimated stick-slip coefficient of friction were calculated to be 0.149 for the Dicronite-Aluminum set, 0.336 for the Aluminum-Aluminum set, and 0.866 for the Plasmadize-Aluminum set. The order of magnitudes for these results was expected, Dicronite having the lowest coefficient, and Plasmadize having the highest. However, it is interesting that the coefficient of stick-slip static friction was calculated to be higher than the regular coefficient of static friction for each material pairing.

One must take into account the difficulty in estimating these values accurately. The displacement data only shows displacement before and after vibration occurs. So, in reality, there is no way to know exactly how much displacement occurred during vibration (only the beginning and end results are known). One can only assume that the displacement that occurred in the friction joint is that which was measured even though in reality this may not be so. This may serve to explain why the measured coefficient of static friction was lower than the calculated stick-slip coefficient of friction.

During vibration testing one sample did not fail as projected, not even at the highest levels of vibration allowed by our test parameters, and not all samples failed to the same degree. This discrepancy may be attributed to surface defects on the friction joint's mating surfaces, and the slight differences in preload for each sample. The position of each assembly on the vibration bed did not seem to be a factor in causing these discrepancies.

In retrospect, accelerometers should have been installed on every single dynamic assembly. Better estimates for stick-slip static coefficient of friction would have been reached this way. Also, if time had not been an issue, it would have been interesting to test several sets of each type of coating (especially Dicronite) at different preloads in order to determine whether preload levels affected the test results—tests have shown that Dicronite coating performance is a function of load (as well as environment, and speed) [5].

GRMS accelerometer data is not shown for the Aluminum-Plasmadize set because of an error during experimentation. This set was the first to have been tested. Initially, the accelerometers were placed on the outside surface of the mass on each of the four samples. This position was offset from the actual C.G. of the sample, so the measured GRMS values were higher due to the accelerometers picking up data from twisting modes of movement of the lever arm. After eight vibration runs this error was discovered and fixed by shifting the accelerometers to the positions described in the configuration section. Due to time constraints, this set of data was not repeated, and GRMS values for the first eight runs were simply estimated.

4. SECOND STATIC TEST

4.1 Methodology

Once each assembly group is removed from the vibration fixture, both masses are removed from each assembly. Particular care was taken to insure that the preload was not changed from the vibration set-up to the static set-up. The friction joints were not disassembled in order to preserve any potential galling that may have occurred during vibration testing. The load cell is checked, and the load is recorded for each assembly. The same procedure and general testing configuration that is used for the first static test is used for the second static test (see Figure 4).

4.2 Data and Results

The preload readings from the load cells as well as the loads required for slip are recorded and used to calculate the coefficient of static friction once again (see Table 4).

Table 4. Average coefficients of static friction, post-vibration test.

Sample	Preload (measured post-vibration)	Average Coefficient of Friction	Standard deviation
Dichronite	~8150 lbs	0.296	0.069
Aluminum	~3400 lbs	0.683	0.033
Plasmadize	~850 lbs	0.846	0.082

4.3 Discussion

The second static test was carried out to verify whether the coefficient of static friction would change as a result of vibration testing. The data indicates that a change did occur. Note that the values for the second static coefficient of friction are higher than those from the first test. This is possibly due to abrasions, galling, and/or cold welding between the mating surfaces which may have occurred during the vibration tests (see Figure 18). The difference between the first and the second static friction coefficient is greater for the Aluminum-Aluminum and Dicronite-Aluminum sets than it is for the Plasmadize-Aluminum set. This indicates that abrasions and surface damage of Plasmadize coatings does not greatly affect the tribological behavior of the material. This makes sense since Plasmadize coatings are already rough in nature to begin with.

The second static coefficient results for the Dicronite coated set, measured at about 0.3, indicate that the Dicronite coating saw enough wear to expose the aluminum surface where even more galling occurred. This becomes apparent when the 2^{nd} static coefficient of the Dicronite set (0.3) is compared with the 1^{st} static coefficient of the Aluminum-Aluminum set (0.2). Notice that these two values are very close.

The Plasmadize-Aluminum set shows that in two of the comparisons the stick-slip coefficient of friction is greater than all others. However, the 2^{nd} static coefficient measurements are very close to the stick-slip coefficients and this result may be attributed to the GRMS data that was used to estimate the stick-slip coefficients (as explained in section 3.4).

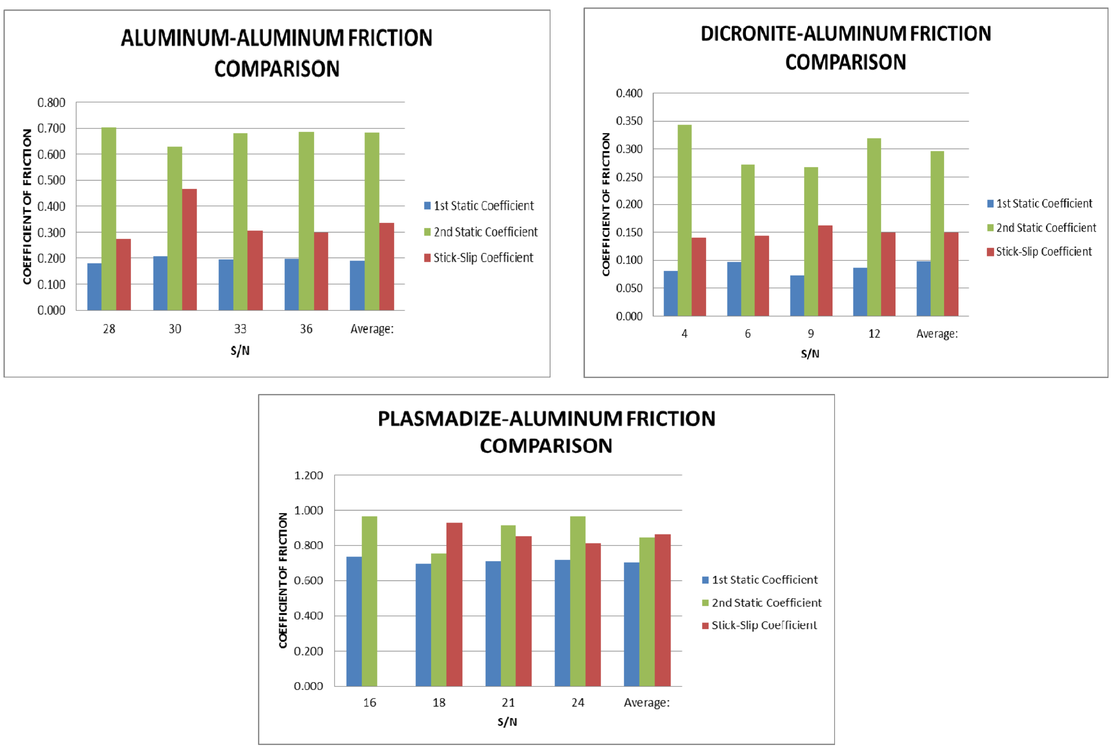


Figure 18. Comparison of coefficients of friction for all three tests.

5. SURFACE GALLING AND CONTAMINATION

After all data was collected, assemblies were taken apart and tested for contaminants, debris, and galling. There was no visible or significant contamination outside of the area of contact. All debris seemed to cake and stick to the contact surfaces in the form of a dark ring composed of Aluminum Oxide. This effect was most noticeable in the Plasmadize samples, which displaced the least during the random vibration test.

There seemed to be no apparent correlation at all between aluminum oxide markings and large displacement during vibratory testing (see Figure 19). However, nearly all samples had some residue; the Dicronite set being the least visibly damaged, followed by the bare aluminum set (see Figures 20-21).

Figure 19. (Left) Evidence of galling.

Figure 20. From left to right: High, medium and low displacement in Plasmadize samples.

Figure 21. From left to right: High, medium, and low displacement in Dicronite samples.

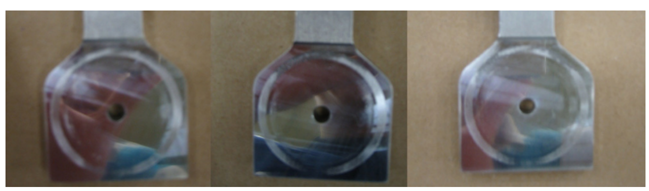


Figure 22. From left to right: High, medium, and low displacement in bare aluminum samples.

6. MATHEMATICAL EQUATIONS

6.1 First Coefficient of Static Friction

- The torsion applied is 4.50 x the applied load (P) = 4.5P
- The shear resisted by torsion, V_T , is T/r, wherein r is 1.375/2 = 0.6875
- The shear resisted by shear is P
- The applied load needed to overcome static friction is as follows:
  - $V_T + V_V$ = Shear applied to ring
    - V_T = 4.5P/.6875 = 6.545P
    - V_P = P
    - RSS: SQRT((P^2)+(6.545P^2))=6.62P
  - Shear capability is μN, wherein μ = coefficient of friction and N is the applied preload
  - μN = applied shear = 6.62P
  - Therefore the point at which the sample will start to slip is when
    P = μN/6.62

$$\mu = 6.62P/N \tag{1}$$

6.2 Coefficient of static slip-stick friction

- Equivalent static load is…
  - The torsion applied is (4.78)(G load)(3.75) = 17.95 G
  - The shear resisted by torsion, V_T , is T/r, wherein r is 1.725/2 = 0.8625
  - The shear resisted by shear is 3.75 G
  - The applied load needed to overcome dynamic friction is as follows:
    - $V_T + V_V$ = Shear applied to ring
      - V_T = 17.95 G/.8625 = 20.81 G
      - V_P = 3.75 G
    - Shear capability is μN, wherein μ = coefficient of friction and N is the applied preload
    - μN = applied shear = 21.15 G
    - Therefore the coefficient of dynamic friction can be calculated by using the G load at which slip occurs (3*GRMS)

$$\mu = 21.15G/N \tag{2}$$

6.3 Second coefficient of static friction

Calculations are the same as those for the first coefficient of static friction, except for the diameter of the contact surface. By adjusting for this change, we get:

$$\mu = 5.312P/N \tag{3}$$

7. CONCLUSIONS

A test program was designed and executed to investigate the stick-slip phenomenon in bolted joints in the presence of high-level random vibrations. The aim of the test program was to quantify and characterize the coefficient of static friction that acts on friction joints before stick-slip occurs during random vibratory motion and examine how stick-slip affects the coefficient of static friction of the joints once vibrations have ceased. A series of three tests were carried out to accomplish this task. Specifically, three different material pairings (the contact surfaces for the friction joints) were tested with twelve samples of each of these pairings. These being Aluminum and Aluminum, Plasmadize and Aluminum, and Dicronite and Aluminum.

Data from the first test was used to calculate the coefficient of static friction of the material pairings before any stick-slip or vibratory motion occurred. The test showed that the coefficients of friction for the Plasmadize-Aluminum and Dicronite-Aluminum were higher than expected; 0.098 and 0.704 respectively. Coating differences between manufacturers may account for this unexpected result on the Plasmadize pairings. However, it is likely that the Dicronite high preloads on the Dicronite set affected the results for that pairing[5].

In the second test, the vibration test, all three material pairing sets were exposed to varying degrees of vibration and acceleration and displacement data was gathered on each set in order to determine the friction coefficient in the joint before stick-slip occurs. The average values for the estimated stick-slip coefficient of friction were calculated to be 0.149 for the Dicronite-Aluminum set, 0.336 for the Aluminum-Aluminum set, and 0.866 for the Plasmadize-Aluminum set. The order of magnitudes for these results was expected, Dicronite having the lowest coefficient, and Plasmadize having the highest. However, it is interesting that the coefficient of stick-slip static friction was estimated to be higher than the regular coefficient of static friction, obtained during the first test, for each material pairing (see Figure 18).

The third test was similar to the first test in that it was used to gather data on the coefficient of static friction for the material pairings. However, this test aimed to quantify the coefficient of static friction after stick-slip had occurred, the second coefficient of static friction. The data from this test and the first test were used to characterize the effects of stick-slip on the coefficients of static friction in friction joints (see Figure 18). The data from this test indicated that stick-slip has a large effect on the friction coefficient between joints. The values for the second static coefficient of friction are higher than those from the first test. This is possibly due to abrasions, galling, and/or cold welding between the mating surfaces which may have occurred during the vibration tests.

The difference between the first and the second static friction coefficient is greater for the Aluminum-Aluminum and Dicronite-Aluminum sets than it is for the Plasmadize-Aluminum set. This indicates that abrasions and surface damage of Plasmadize coatings does not greatly affect the tribological behavior of the material. This makes sense since Plasmadize coatings are already rough in nature to begin with. The second static coefficient results for the Dicronite coated set, measured at about 0.3, indicate that the Dicronite coating saw enough wear to expose the aluminum surface where even more galling occurred. This becomes apparent when the 2^{nd} static coefficient of the Dicronite set (0.3) is compared with the 1^{st} static coefficient of the Aluminum-Aluminum set (0.2). Notice that these two values are very close. The Plasmadize-Aluminum set shows that in two of the comparisons the stick-slip coefficient of friction is greater than all others. However, the 2^{nd} static coefficient measurements are very close to the stick-slip coefficients and this result may be attributed to the GRMS data that was used to estimate the stick-slip coefficients (as explained in section 3.4). Practically speaking, what the data indicates is that once stick-slip occurs, it becomes less likely for the friction joints to move back to their initial position as galling in the mating surfaces increases the friction encountered by the joint.

Dicronite coatings provide low friction interfaces, and thus, should not be used in applications where stick-slip is unwanted. Plasmadize coatings provide high friction interfaces, and provide more security than bare aluminum friction joints. However, when designing optical devices, it is best not to use friction joints for parts in which alignment is critical. The stick-slip phenomenon is not easy to predict and may happen during random vibration. Variability for the coatings tested (except Plasmadize), are too great to make an accurate estimate during the design process.

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REFERENCES

[1] R.I. Leine and D.H. van Campen and A. de Kraker and L. van den Steen, “Stick-Slip Vibrations Induced by Alternate Friction Models”, Nonlinear Dynamics, 16(1), 41-54 (1998)

[2] Andersson, I., “Stick-slip motion in one-dimensional continuous systems and systems with several degrees of-freedom”, Ph.D. Thesis, Chalmers University of Technology, Göteborg, Sweden, (1980)

[3] Awrejcewicz Jan and Olejnik Pawel, “Occurrence of Stick-Slip Phenomenon”, Journal of Theoretical and Applied Mechanics, 45(1), 33-40 (2007)

[4] Avitabile, Peter, Chris Niezrecki, and Mark Helfrick, "Noncontact Measurement Techniques for Model Correlation", Sound & Vibration, 44(1), 8-13 (2010)

[5] Anderson, M. J. and Cropper, M., and E. W. Roberts, “The Tribological Characteristics of Dicronite”, Proc. 12th Euro. Space Mechanisms & Tribolgy Symp. 653, 19-21 (2007).